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ORIGINAL PAPER

Candidate site selection for nuclear power plants in Saudi Arabia using GIS

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Abstract
Many countries prefer to use renewable and clean energy sources over fossil fuels as fossil fuels are limited and have a negative impact on the environment. Although there are diverse, renewable, and clean sources of energy, such as solar, wind, and geothermal, the low and variable productivity of these resources impedes their application. Conversely, nuclear energy is a reliable, stable, and safe source of energy. The International Atomic Energy Agency recommends the use of geographic information systems in site planning of nuclear plants. Accordingly, this study seeks to apply the technical capabilities of geographic information systems in building a geographical database as well as data processing and analysis to support the decision making and examination of suitable sites for nuclear reactor facilities. In this study, a spatial suitability analysis methodology based on the multi-criteria decision-making method was used to identify candidate areas with suitable spatial characteristics for nuclear reactor facilities in the Kingdom of Saudi Arabia. Moreover, vector modeling was used to successfully determine potential sites over an area of ~ 4442 km^2 on the eastern coast (Al-Ahsa, Al-Adaid Governorate) and over an area of ~ 600 km^2 on the western coast (Umloj, Yanbu, Rabigh, Al-Laith, and Baysh) of the Kingdom.

Keywords Nuclear power plants · Suitability analysis · GIS · Saudi Arabia

Introduction and background

Fossil fuels such as coal, oil, and gas remain the primary sources of energy and electricity in many communities. However, the combustion of fossil fuel is believed to be one component responsible for the acceleration of global warming, which could be catastrophic for life. Nevertheless, as the world depends on energy, it is moving away from the use of fossil fuels toward discovering more clean and sustainable sources (Alnuaimi 2015).

Many countries are exploring the adoption of renewable energy sources, such as solar, wind, and geothermal, and methods to bring them to high levels of reliability and availability. Until availability considerations of renewable energy sources are solved, nuclear energy could help nations in diversifying their energy sources. For example, the fission of a metric ton of uranium provides a thermal energy equivalent to that obtained from the combustion of 3 million tons of coal or 12 million barrels of oil. The world's oil and natural gas reserves have been estimated to be depleted by 2100 (Comby 2006). Considering such an estimate, in the future, the world may need to adopt nuclear energy at a larger scale. However, locations for nuclear plants should be selected wisely to mitigate the possible impact of radiation accidents and to reduce the cost of their integration within the electric power grid.

The selection and evaluation of suitable sites for the establishment of nuclear plants is a crucial and necessary step and can significantly affect the costs involved and the acceptance from local populations, as well as the safety of the facilities during operation. The results of this step determine the success of an entire nuclear energy project. Poor planning and lack of information may lead to wrong decision-making and cause significant delays and long periods of closure (International Atomic Energy Agency; IAEA 2015).

Spatial suitability analysis for the purpose of nominating sites on which to establish nuclear plants is a multi-faceted approach that includes technical considerations such as the availability of cooling water, safety, and the ramifications of external hazards

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(seismic, volcanic, and geotechnical), such that sites with significant external risks may be determined for exclusion. Additionally, site determination operations aim to reduce the effects of potential accidents on the population and environment. To this end, the possibility of implementing emergency plans in the event of an accidental release of radioactive elements is considered, given the terrain, the distribution of the population, and the infrastructure that would facilitate the implementation of the emergency plans (Martins et al. 2011).

From the above discussion, the development of a spatial suitability analysis clearly requires the acquisition, organization, and management of a large amount of data on a potential reactor site. Considering their capabilities of storing, organizing, and managing a large amount of data through geographical databases, geographic information system (GIS) technologies are expected to play a major role in site selection, as they can support data analysis and decision-making and are directed toward solving specific problems (El-Sayed 2015).

Several studies have dealt with the issue of selecting sites for nuclear plants. To address the goal of producing 300 GW of electricity with nuclear energy by the year 2050 in the United States of America (USA), Mays et al. (2012) applied spatial data modeling and GIS to determine appropriate reactor locations. Abdel-Latif (2008) considered the performance of various spatial decision-making models in determining the appropriate location for the construction of a nuclear power plant in the eastern Province of the Kingdom of Saudi Arabia. In China, Wu (2012) conducted a study on selecting the optimal location for nuclear power stations based on an analytical hierarchy process (AHP), and in Malaysia, Idris and Abd Latif (2012) directed a study using multi-criteria GIS to select a suitable reactor location based on the role of an analytical hierarchy process (AHP) in determining the best location for a nuclear power plant. Goldfarb (2013) conducted a study that is aimed at evaluating the present and past nuclear reactor sites in California (USA) based on a number of factors and considering the risks that threaten these stations. In Egypt, Abudeif et al. (2015) conducted a multi-criteria decision analysis based on a hierarchical analysis in a GIS environment to locate a nuclear power plant. In Iran, Jafari et al. (2015) conducted a study on the location of a nuclear power station, using GIS, in which the weighted linear combination method was applied to identify the optimal locations of nuclear power stations in Hormuzgan Province located on the Strait of Hormuz to determine the most feasible site that complies with the standard requirements of the IAEA. In Brazil, the strategy of the Brazilian Energy Plan (PNE 2030) is to expand energy supply by 2030. As such, Martins et al. (2011) presented a study on the site selection process for nuclear power plants to support the decision-making process and improve public participation. In 2016, Barzehkar et al. conducted a study seeking to select a site for a nuclear power plant in the coastal region of Gilan Province (Sahar Khiz), Iran, given the natural potentials and restrictions in the region, besides the regulatory regulations set by the IAEA, and in Turkey, Baskurt and Aydin (2018) conducted a methodology for detecting suitable areas in Edirne, using GIS by spatial analysis based on filtering criteria (screening criteria).

This literature review demonstrates the role of GIS in determining suitable sites for nuclear plants. Although these studies differed in their methodologies, they also provide the foundation for choosing the appropriate method. And it reported the suitability of the Boolean logic method in the initial estimates for filtering the appropriate areas based on the exclusion criteria (restrictions) so that a preliminary filtering is conducted to exclude the areas that prevent the construction of the nuclear power plant, which leads to a reduction in the study area, and thus, more complex methods can be implemented with more standards. Accuracy, after reducing the study area, the second type can be adopted, which are the discretionary criteria, which are called factors, and are used based on fuzzy logic. Therefore, these studies provide an applied methodology that supports future studies.

It is hoped that this study will be a spatial cognitive addition. Since the issuance of a royal decree in 2010 that stipulates the necessity of making use of nuclear energy to help meet the increasing demand for electricity in the Kingdom of Saudi Arabia, conducting studies to determine the suitability of the Kingdom's lands and nominate suitable sites for building nuclear power plants has been necessary. However, no existing studies that focus on Saudi Arabia have adopted the IAEA methodology.

Study area

The present study covers the entire Kingdom of Saudi Arabia (Fig. 1), located in the far southwest region of the Asian continent. With an area of about 2 million km^2, the Kingdom occupies four-fifths of the Arabian Peninsula and supports a population of approximately 31,742,308 people (General Authority for Statistics 2016).

Methodology and processing

The present study applied the spatial suitability analysis approach based on the multi-criteria decision-making method (Dyer et al. 1992; Abdel-Latif 2008; Mays et al. 2012; Goldfarb 2013; Barzehkar et al. 2016; Baskurt and Aydin 2018; Voogd 1983) to select candidate areas with spatial features appropriate for nuclear plants in Saudi Arabia. The methodology can be divided into six stages, namely, general design, regional analysis, construction of a geodatabase, building a suitable model, generating a suitability map, and exporting the proposed model.

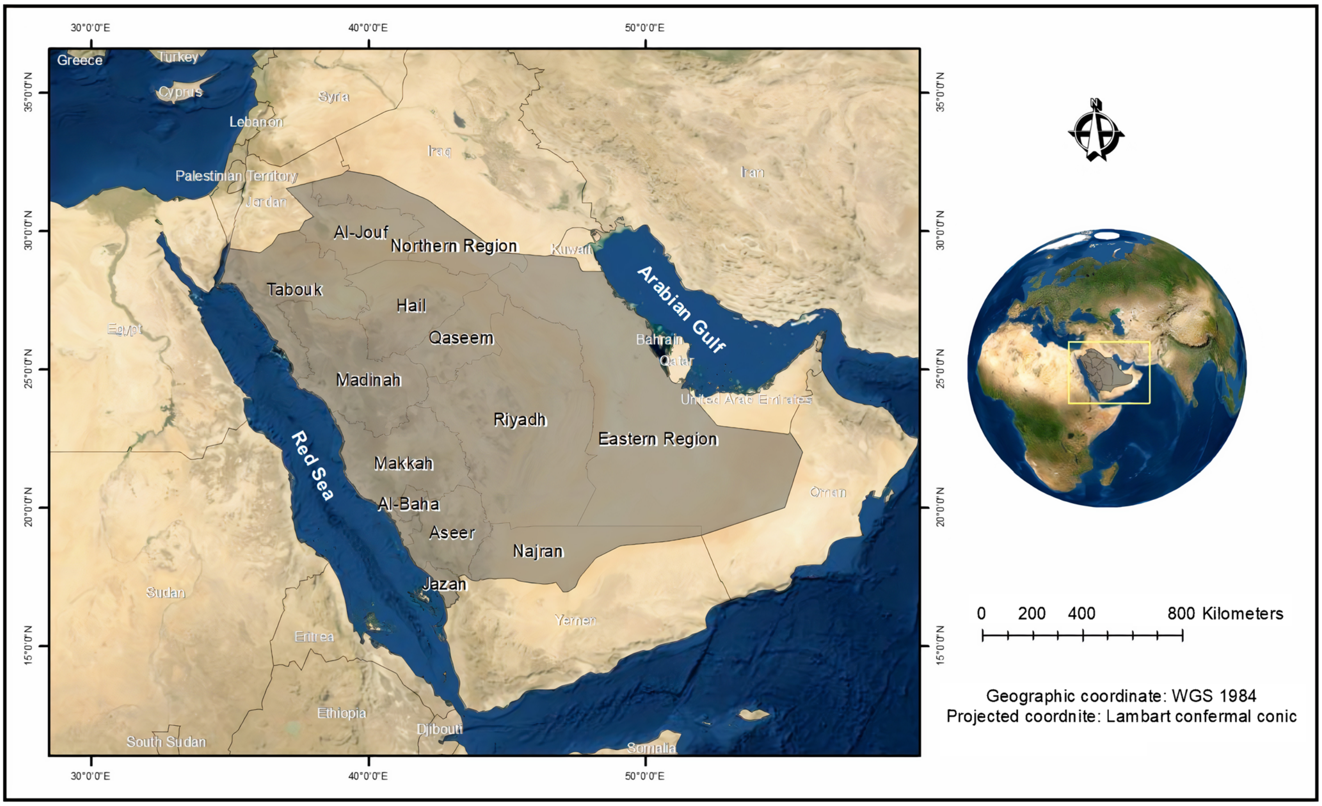


Fig. 1 Study area

Stage one: general design

This stage encompasses a description of the theoretical framework of the model in which aspects of the subject are comprehensively identified, from which the scope of the study is then determined. This is one of the most important stages of the preparation of the site suitability model, as it provides an integrated picture of the subject and explains the aspects addressed in this study. The data required for this study were determined by establishing the objective scope (Fig. 2).

Stage two: regional analysis

The criticality of water

The criterion of the availability of cooling water is an essential technical constraint, as large volumes of water are required during the operation of a nuclear reactor. Nuclear plants require 50 m^3/s of cooling water per 1000 MW, and for a reactor producing 1600 MW of energy, the flow rate of cooling water is 280,000 m^3/h. Considering this, proximity to abundant and

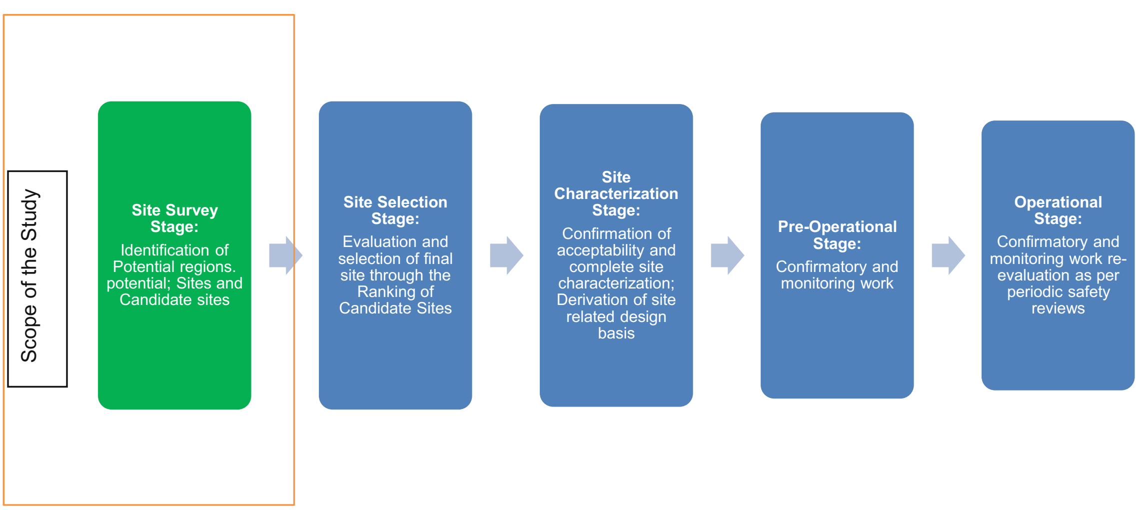


Fig. 2 Flow chart for nuclear reactor site selection through operation as established by the IAEA (2015)

constant water sources is pivotal in deciding the location of a nuclear reactor (IAEA 2012). Regional analysis was conducted to identify potential site areas based on the availability of cooling water, and the eastern and western coastal areas were identified as ideal candidates (Fig. 3).

Screening

In this step, potential areas are examined for the selection of candidate sites. The main objective here is to exclude unsuitable areas based on all safety and other non-safety considerations by application of exclusion criteria. These criteria are important because they are linked to natural phenomena, risks, and geographical issues that do not have possible engineering solutions (Fig. 4).

Evaluation, comparison, and ranking

The purpose of this third step is twofold: (1) to evaluate the sites in order to ensure that there are no features at the sites or in their surrounding areas that would preclude the construction and operation of a nuclear installation and (2) to compare the candidate sites and rank them in order of their attractiveness as possible sites for nuclear installation (Table 1).

Geographical overview of potential reactor sites

Potential plant sites are located along the east and west coasts of Saudi Arabia, with each region supporting variable geographical features. In the west, a possible siting area with a 2400-km-long coast overlooks the Red Sea and the Gulf of Aqaba, covering an area of approximately 62,700 km^2. This region comprises the Tehama Plain, which is confined between the western highlands to the east and the Red Sea coast to the west. Additionally, this area serves as a transition between the shelf of the Red Sea and the high mountains of Al-Jarf which expand toward the south, bordering the city of Jizan up to approximately 40 km. To the north, the Tehama Plain narrows until it disappears near 26° N latitude, south of Al Wajh. Furthermore, the coastal plain is crossed by valleys characterized by steep slopes and deep streams that flow into the Red Sea (Saudi Geological Survey 2017).

The eastern region overlooks the Arabian Gulf and comprises a flat plain that begins its extension from the Kingdom's borders with the State of Kuwait in the north, north of Ras Al

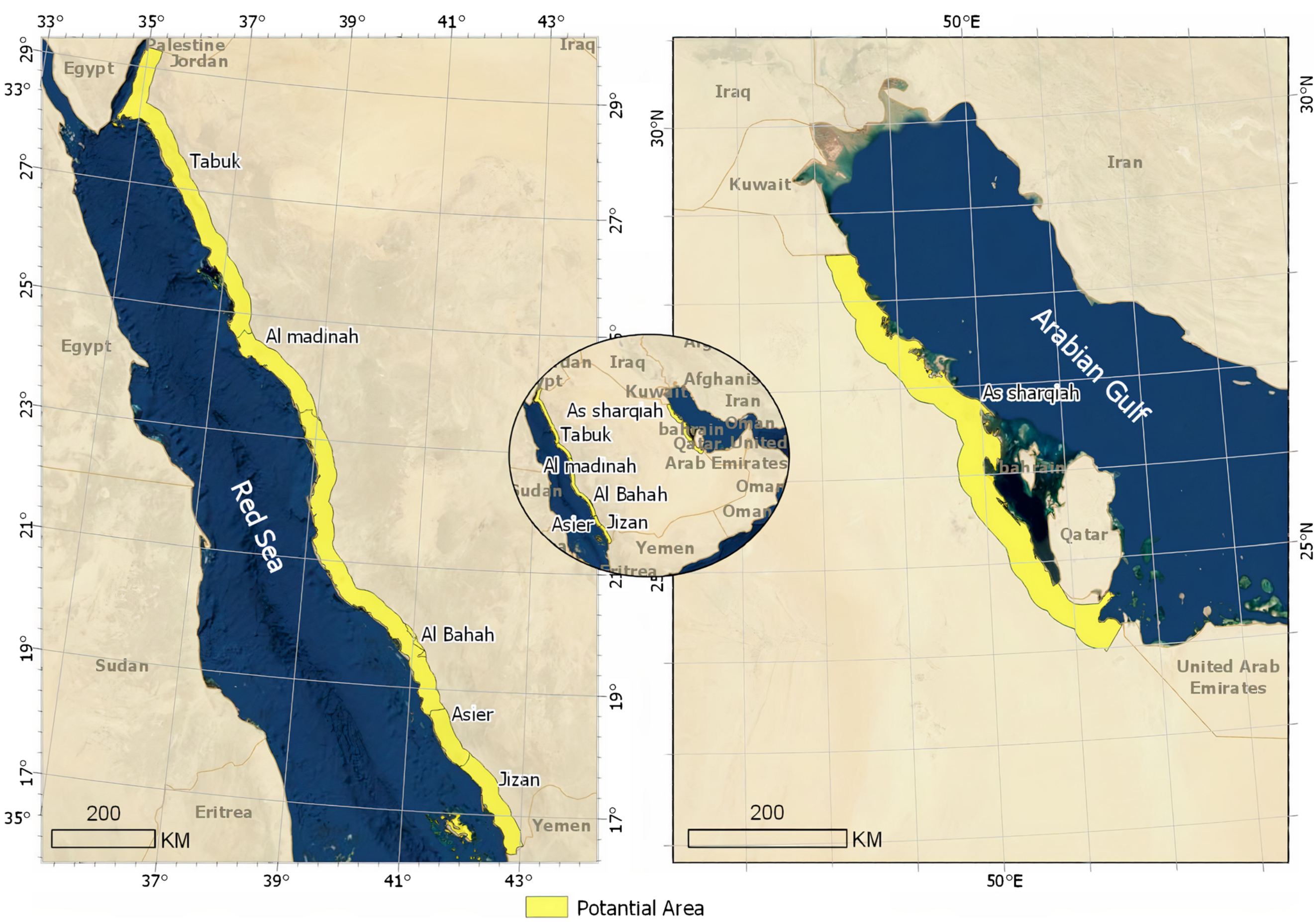


Fig. 3 Potential reactor sites with permanent sources of cooling water

Fig. 4 Main elements of the selection criteria

Khafji, to its borders with the State of Qatar. The length of this plain with its arches is more than 1000 km. The area of potential siting on this plain is estimated at 26.130 km^2. This region is distinguished by the absence of valleys and mountainous hills (Saudi Geological Survey 2017).

Stage three: construction of a geodatabase

The process of building a geographic database is one of the most demanding stages in the work as the outputs of the analysis depend on it, and it was conducted through four main stages:

- collection of data on potential areas,
- constructing geographical databases,
- initial data processing, and
- processing data according to specified standards.

Stage four: building a suitable model

In this stage, layers representing the criteria are applied, necessary geoprocessing operations are conducted, and the spatial analysis (overlay) is then conducted using ModelBuilder (included within ArcGIS Pro). ModelBuilder is an operational tool for creating geographical processing models that automate GIS workflows and can handle sophisticated spatial analyses through which a large amount of work can be conducted quickly and efficiently such that the outputs of the analytical processes can be used in other operations. It is considered a visual programming language and a workflow schematic model that can also be saved and run as a tool within ArcToolBox (Law and Collins 2019).

After specifying the inputs of the spatial data in the previous stages and building a corresponding geographic database, a spatial relevance model is constructed through the following processes:

1 translating the criteria into accurate indicators (determining the spatial sanctuary necessary for each phenomenon) and
2 conducting the overlay process.

Following the addition of the layers to ModelBuilder, a Buffer tool was added, and necessary distances between each feature and a nuclear reactor were entered for each layer. Subsequently, the overlay was conducted by relying on tools that work on the principle of Boolean logic, specifically the Union tool. The outputs of these analyses represent excluded areas.

Stage five: generating a suitability map

At this stage, the model is run and a suitability map is produced (Fig. 5).

Stage six: exporting the proposed model

To facilitate the handling of the proposed model, a tool was designed with a simplified interface that enables users to add their data and conduct a spatial fit analysis quickly, easily, and efficiently for two main objectives:

1 To ensure applicability to other study areas. Users should be able to insert the layers of their study area and then run the tool to conduct necessary geographical operations and obtain the output, i.e., the candidate sites for nuclear plants
2 To verify spatial suitability over future years for the current study area, considering the variability of geographical data over time in anticipation to any geological phenomena that may occur in the study area

Table 1 Screening and ranking criteria for the purpose of site selection (IAEA 2015)

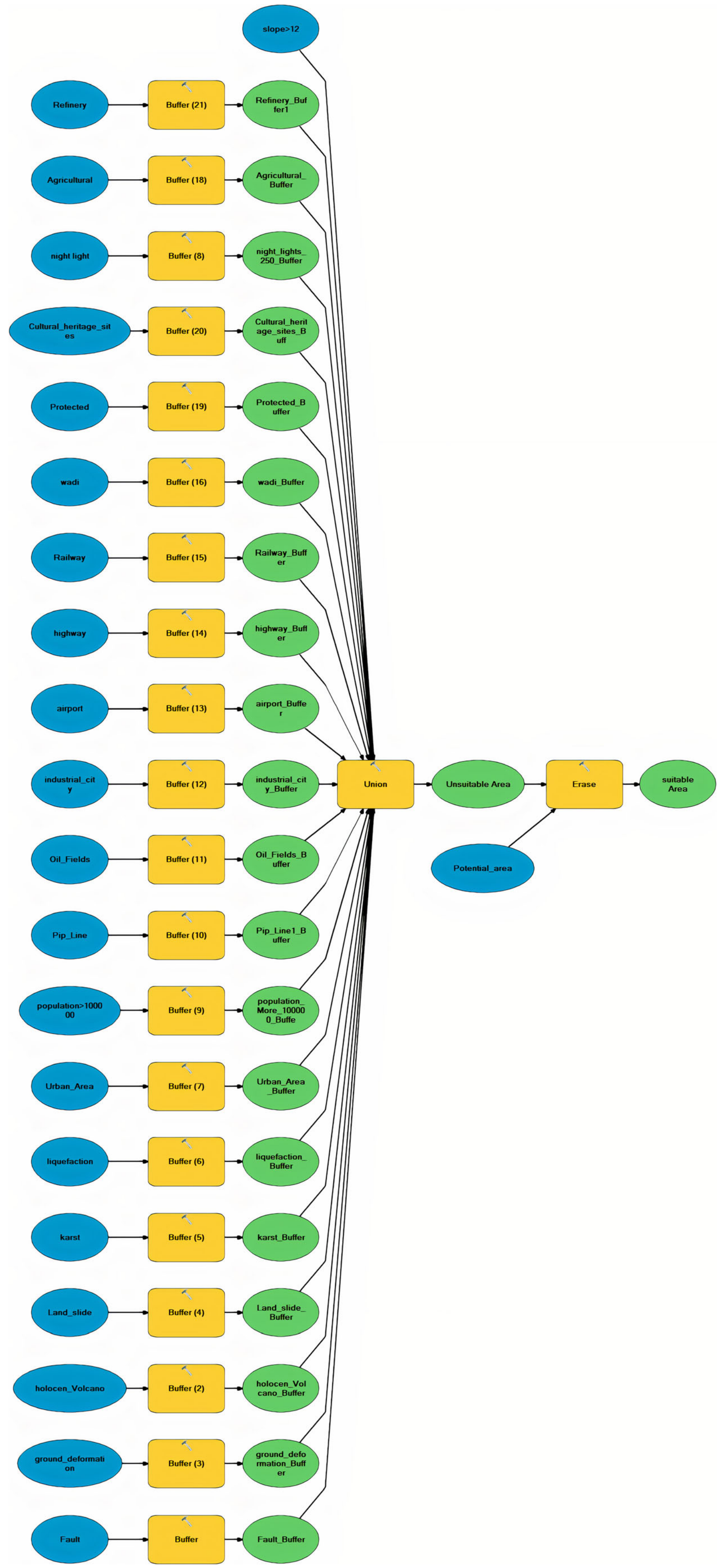
Primary	Type	Screening		Ranking
		Exclusionary	Discretionary	
Earthquake	Ground vibration		✓	✓
	Faults	✓		
Geotechnical	Slope instability (massive landslide)	✓		
	Slope instability (minor)		✓	✓
	Subsidence		✓	✓
	Massive Liquefaction	✓		
	Liquefaction		✓	✓
	Karst (massive)	✓		
Volcanism	Lava flow	✓		
	Pyroclastic flow	✓		
	Ground deformation	✓		
	Tephra Fall		✓	✓
	Volcanic gasses		✓	✓
	Lahars (massive)	✓		
Flooding	River		✓	✓
	Dam break		✓	✓
	Coastal (storm surges, waves, etc.)		✓	✓
	Tsunami		✓	✓
Extreme meteorological events	High straight winds		✓	✓
	Tornadoes		✓	✓
	Tropical storms		✓	✓
	Precipitation		✓	✓
	Sandstorms and dust storms		✓	✓
Human induced events	Aircraft crashes		✓	✓
	Explosions		✓	✓
	Gas releases		✓	✓
	External fires		✓	✓
	Electromagnetic interference		✓	✓
Dispersion	in air and water		✓	✓
Feasibility of implementation of emergency plan		✓		
Implementation of emergency plan			✓	✓
Non-safety	Topography		✓	✓
	Availability of cooling water	✓		
	Access to water		✓	✓
	Access to national or regional electricity grid		✓	✓
	Non-radiological environmental impacts	✓		
	Socioeconomic impacts		✓	✓
	Land use planning		✓	✓

A user interface for this tool is designed and inputs are set according to the names of phenomena that represent exclusionary criteria, such that decision-makers can enter their updated data and run the tool to determine the candidate sites according to the updated data.

Results

In the present study, a model was built, inputs and processes were set, and the model was run to determine the candidate sites in the eastern (Al-Ahsa, Al-Adid, Al-Nairiya, and Al-

Fig. 5 ModelBuilder processing



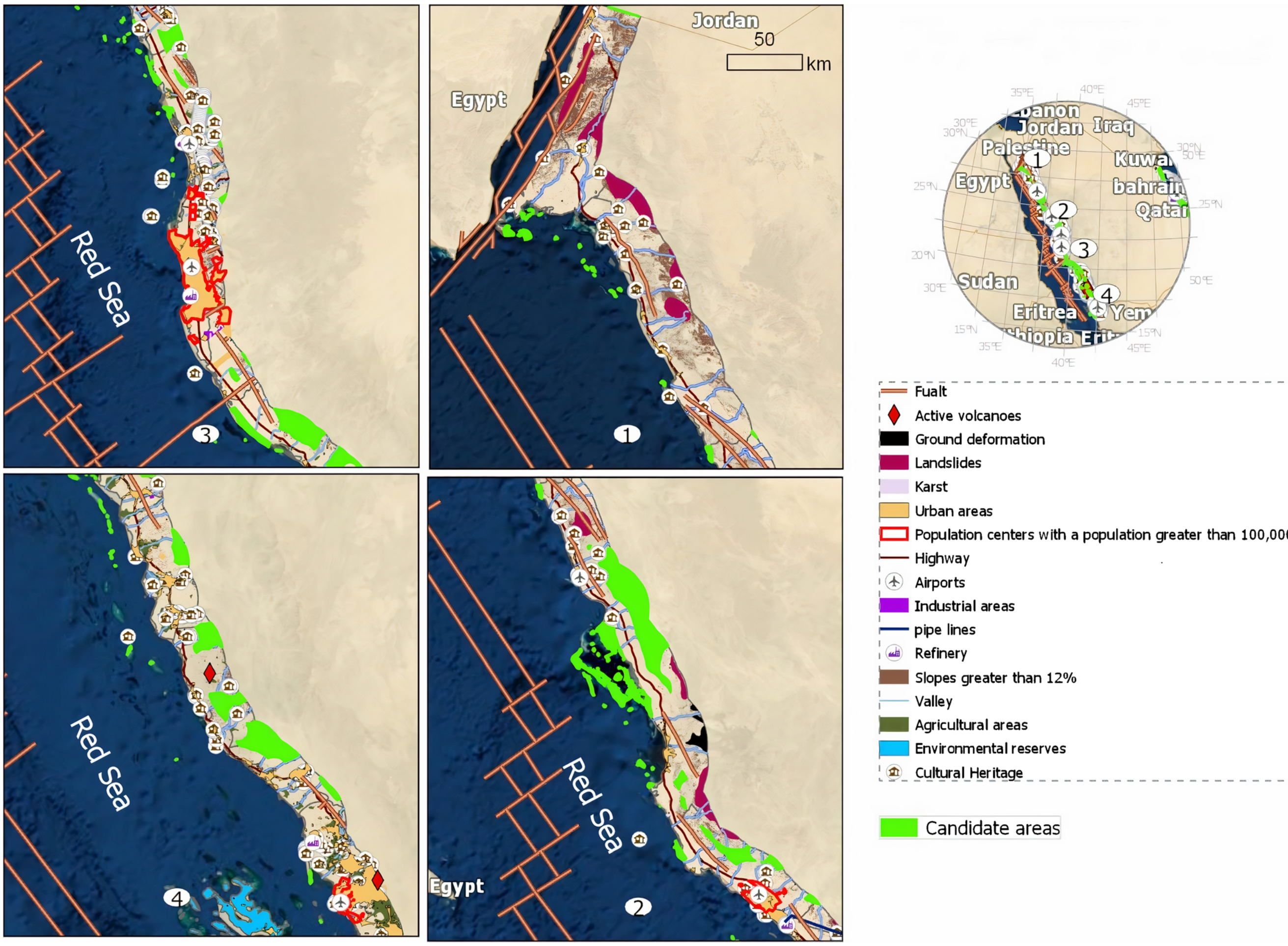


Fig. 6 Criteria considered in excluding some potential reactor sites on the west coast

Khafji) and western regions (Haql, Al-Bida, Daba, Al-Wajh, Umluj, Yanbu, Badr, Al-Leith, Makhwah, Al-Qunfudhah Islands, Muhayil, Abha, Jazan, Al-Darb, and Farasan).

Given the candidate geographical locations, several questions can be raised to filter the results of the analysis, as follows:

- Are the candidate sites consistent with the vision of the Kingdom of Saudi Arabia, or are they inconsistent with its future projects?
- For sites that are not located directly at the source of the cooling water, can the cooling water be pumped through underground pipes?
- Is the area of the candidate sites compatible with the space required for building the stations?

Excluded sites

Excluded sites on the west coast

Although there are common criteria that played a large role in excluding sites in the eastern and western regions of the Kingdom of Saudi Arabia, the western potential areas were particularly characterized by criteria for natural hazards (seismic, volcanic, and geotechnical). These criteria played a major role in excluding many sites that are considered geologically unstable, as they contain an abundance of faults associated with the movement of the Arabian Plate, including its drift away from the African Plate at a rate of 2 cm/year that results in seismic activity along the axis of the Red Sea (Saudi Geological Survey 2018).

The western regions are also characterized by the presence of active volcanoes in the south (Al-Wa'bah and Jabal Yar volcanoes), besides the rough surface topography in most of areas due to steep mountainous slopes and an abundance of valleys. These conditions are considered unfavorable to the adopted emergency plan and would threaten the integrity of a nuclear reactor. Additionally, various sites on the west coast were excluded due to the potential for disrupting implementation of an emergency plan (distance from urban centers) and considering the size of the population and hazards of human-induced events, agricultural areas, and non-safety standards (reserves, historical sites). The criteria according to which some potential areas on the west coast were excluded as shown in Fig. 6.

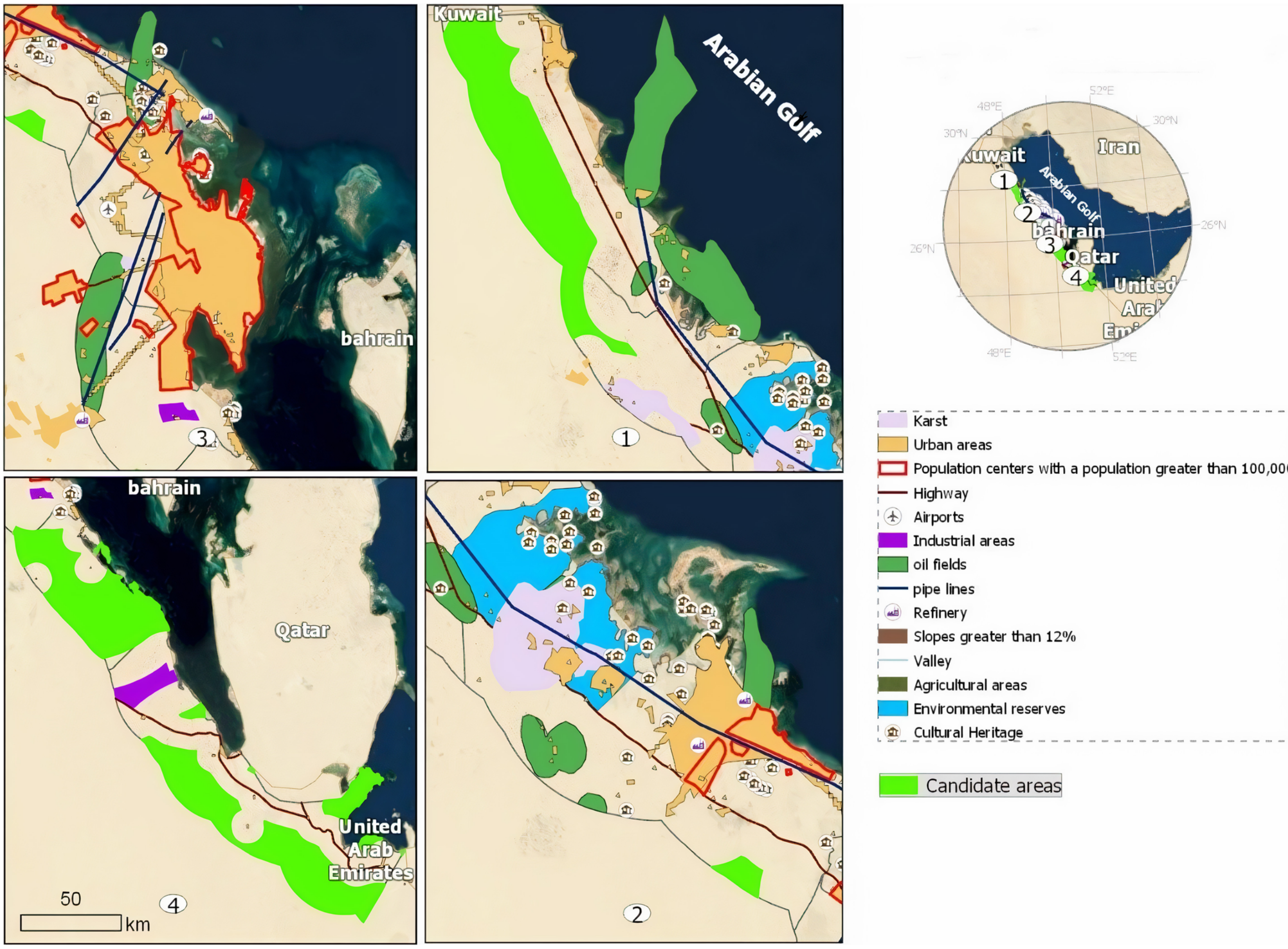


Fig. 7 Criteria considered for excluding some potential areas on the east coast

Excluded sites on the eastern coast

The eastern regions of the Kingdom of Saudi Arabia are characterized by low elevation and flat surfaces, besides a scarcity of valleys. This region is part of the Arab shelf in the Arabian Gulf, with sedimentary formations bearing water and petroleum, and accordingly, large areas were excluded due to the frequency of potentially hazardous human activities such as oil drilling and related infrastructure use including pipelines, refineries, and petrochemical plants. Other criteria were also considered in the exclusion of various sites on the east coast, such as geotechnical criteria and conditions related to the possibility of disruption of the execution of emergency plans, including the size of the population, distance from urban centers, facilities with potential danger, and agricultural areas, and non-safety standards (environmental reserves, historical sites). The criteria according to which some sites in the eastern coast were excluded are shown in Fig. 7.

Potential candidate sites

Following the application of specific criteria, the analysis produced numerous candidate sites, including Al-Ahsa, Al-Adid, Al-Nairyah, Al-Khafji, Haqal, Al-Bida, Daba, Al-Wajh, Amlaj, Yanbu, Badr, Al-Leith, Al-Makhwah, one of the islands belonging to Al-Qunfudhah, Mahayil, Abha, Jazan, Al-Darb, and Farsan.

However, the analysis required an additional level of screening that would account for major development projects (the Neom and Red Sea Projects), royal reserves, including the Royal Reserves announced in 2018 and the Prince Muhammad Bin Salman Reserve, considerations related to the amount of land required to build the reactor facilities, and the reliability of a water

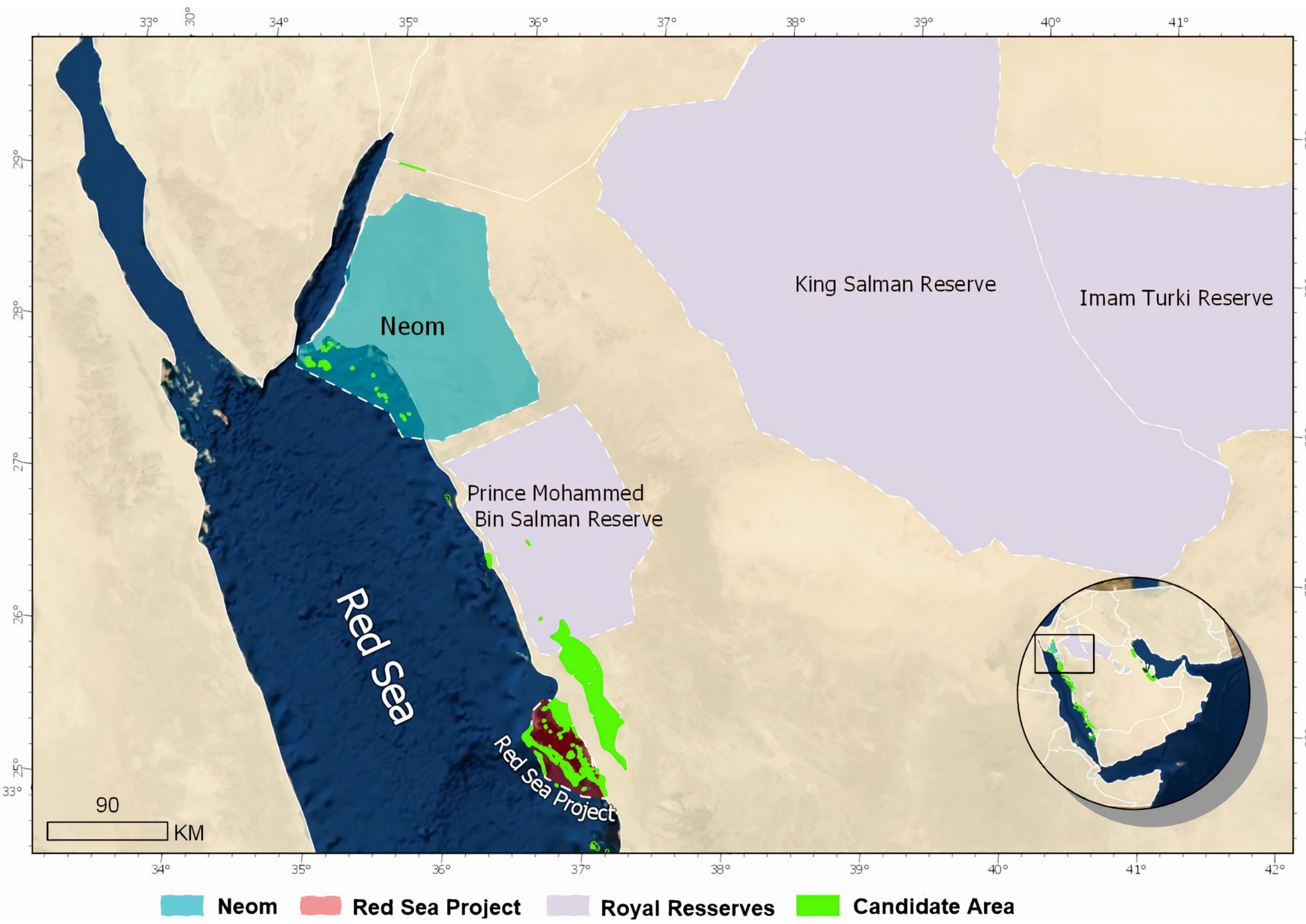


Fig. 8 Future projects and royal reserves

supply to cool the reactor. Therefore, we adopted these considerations to finalize the analysis results (Figs. 8 and 9).

In total, 15 final candidate sites were identified and are shown in Figs. 10 and 11.

Discussion

Candidate sites

Geographically, the reactor candidate sites are distributed in proximity to vital areas of the future projects, industrial cities, and populations according to an established permissible safe limit, which qualifies and enhances enabling atomic energy to contribute to the mixture of useable Saudi national energy. This suggests that nuclear energy can contribute to providing sustainable national development requirements as stipulated in the Saudi Arabia's Vision 2030 according to local requirements and international obligations, which makes atomic energy a significant component of the energy system in the Kingdom of Saudi Arabia and strengthens the Kingdom's role as a leading and active country in the field of energy. Surely, all these nominated sites meet the requirements of the IAEA, particularly the exclusion criteria requiring sufficient area needed to build reactor facilities. Below are the areas of each nominated site in detail.

Candidate sites on the eastern coast

- A site in Al-Ahsa on Uqair Beach, extending to the internal regions, with an area of about 2942 million m^2
- Three sites in Al Udeid Governorate

– Ras Abu Qamis site, with an area of about 1394 million m^2
– A site in the north of Al Udeid Governorate, with an area of about 41 million m^2
– A site in the south of Al Udeid Governorate, with an area of about 65 million m^2

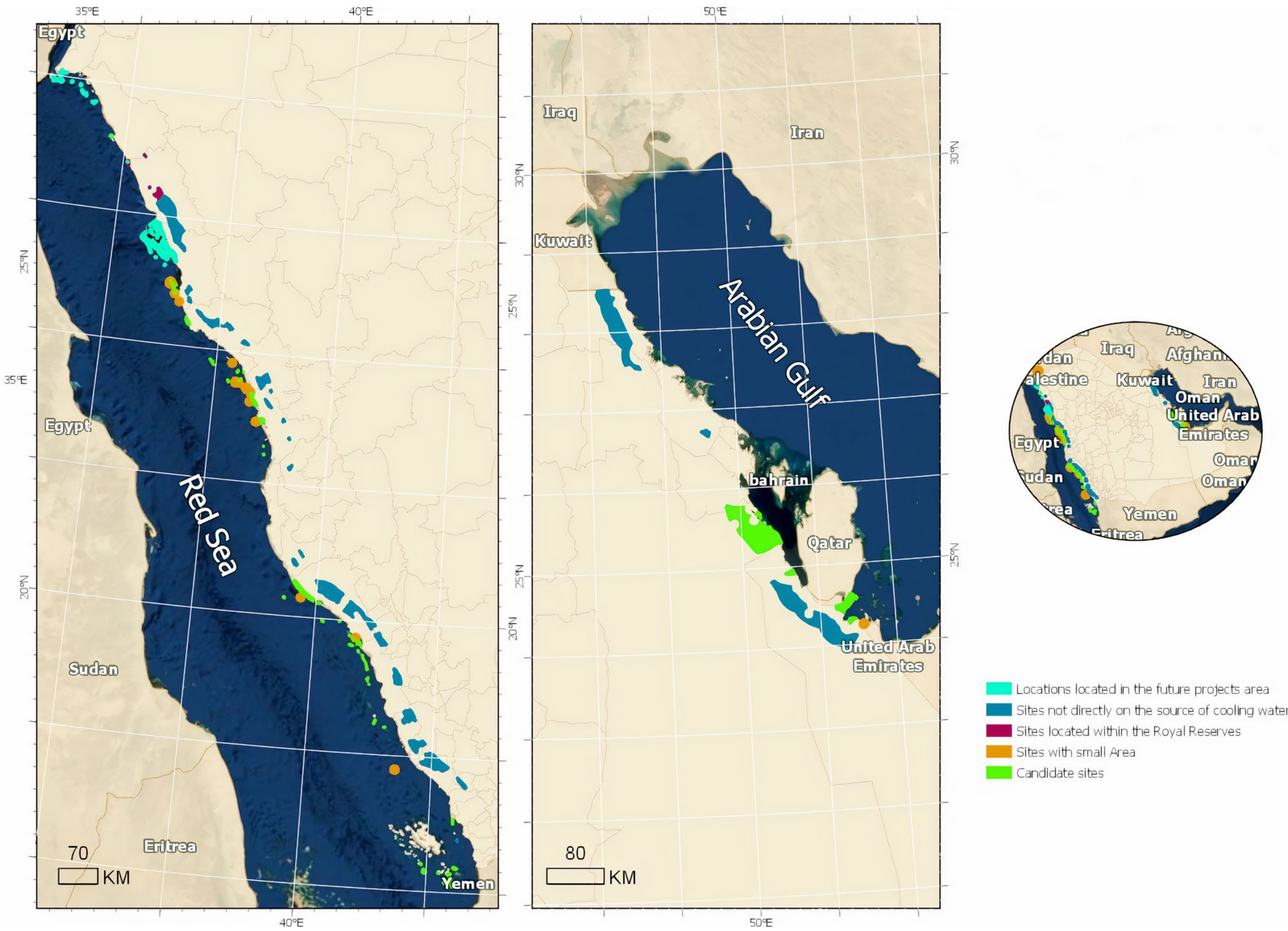


Fig. 9 Filtration of candidate sites through analytical considerations suggested by the study

Candidate sites on the western coast

- A site in Umluj governorate with an area of about 7 million m^2
- A site in Yanbu with an area of about 30 million m^2
- Four sites in Rabigh:

– The first site with an area of about 2 million m^2
– The second site with an area of about 8 million m^2
– The third site with an area of about 17 million m^2
– The fourth site with an area of about 4 million m^2

- A site in Al-Leith governorate with an area of about 230 million m^2
- A site in Baish with an area of about 98 million m^2
- A site in Farasan with an area of about 100 million m^2
- Other sites with an area of about 98 million m^2

The process of selecting the appropriate site for nuclear power plants according to the methodology and requirements of the IAEA goes through several stages: first, identifying the area of interest; second, determining the potential areas based on regional criteria; third, selecting the candidate sites on the basis of the exclusionary criteria; and finally, arranging them according to preference to reach the best sites based on the ranking criteria. A regional analysis was conducted here to identify possible areas on the basis of the availability of cooling water, and the eastern and western coastal regions were identified as significantly potential areas, as the criterion for the distance from urban centers played a major role in excluding large areas on the eastern and western coasts. The western regions were also distinguished by the influence of seismic, volcanic, and geotechnical criteria in excluding many areas therein, as this is related to the geological instability. As for the eastern regions, they have been affected by the criteria related to the facilities that have a potential risk of rejecting many areas, due to the presence of oil refineries and associated facilities.

Discussion of methodology used in the analysis and validation of results

The methodology applied here demonstrated its efficiency in achieving the objective of the study and is characterized by

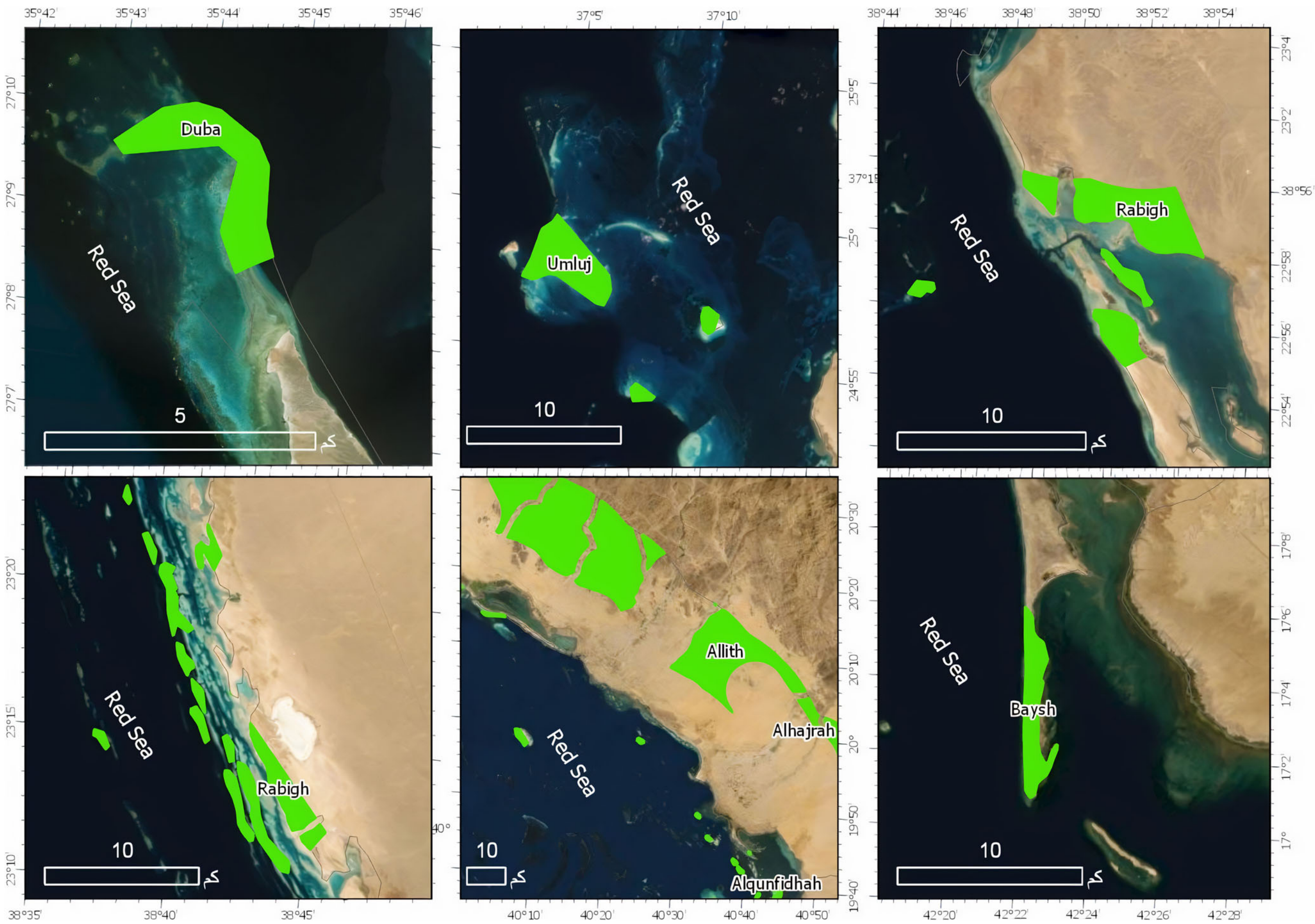


Fig. 10 Final candidate sites on the west coast, including one site each in Umluj, Duba, Yanbu, Al-Lith, and Baysh and six in Rabigh

clarity, rapid achievement, and appropriateness for the initial nomination and judgment of the suitability of the lands of the Kingdom of Saudi Arabia for nuclear reactor facilities, according to the exclusionary criteria, to conduct a process of matching multiple data. Through this method, the rules of Boolean Logic were applied to the spatial and descriptive characteristics of layers using the logical operator (OR), to see if the criteria are met or not.

The findings of the study revealed multiple sites suitable for the construction of nuclear power plants for electricity generation along the east and west coasts of the Kingdom of Saudi Arabia by using a spatial suitability model in ArcGIS pro. A spatial suitability model was created based on many spatial data related to the study criteria and cartographic modeling to serve as inputs to the model. The spatial data sources included topographic maps, satellite images, maps of land use, and geological hazard maps. Clearly, incorrect inputs will result in inaccurate results. Therefore, the study validated the model through three different stages. The first stage is through the Erdas Imagine Swipe Tool that produces a comparison between the model result and recent satellite images; this facilitates a review of the findings and validates any natural or human change processes in the appropriate areas. The second stage is validation by topographical maps of suitable areas through the evaluation of land use, topography, and slope. The last stage involves field validation by on-site visits to some of the nominated areas, inspecting them, and verifying the correct application of standards. Generally, the findings of the study determined the appropriate areas according to the exclusion criteria promoted by the IAEA. This study represents an important initial stage, especially as it is the first to cover the entire area of the Kingdom of Saudi Arabia. Additional future studies are needed to determine the most suitable areas according to other detailed criteria.

Conclusions

Using the spatial suitability analysis approach, candidate sites of nuclear power plants in Saudi Arabia were identified. The results showed many candidate sites along the east and west coasts. The final candidate sites on the west coast are Duba, Umluj, Yanbu, Rabigh, Al-Lith, and Bish, and those on the east coast are Al-Ahsa and Al-Adaid. The study recommends broadcasting the possibility of investing in nuclear energy in these areas, especially considering the increasing

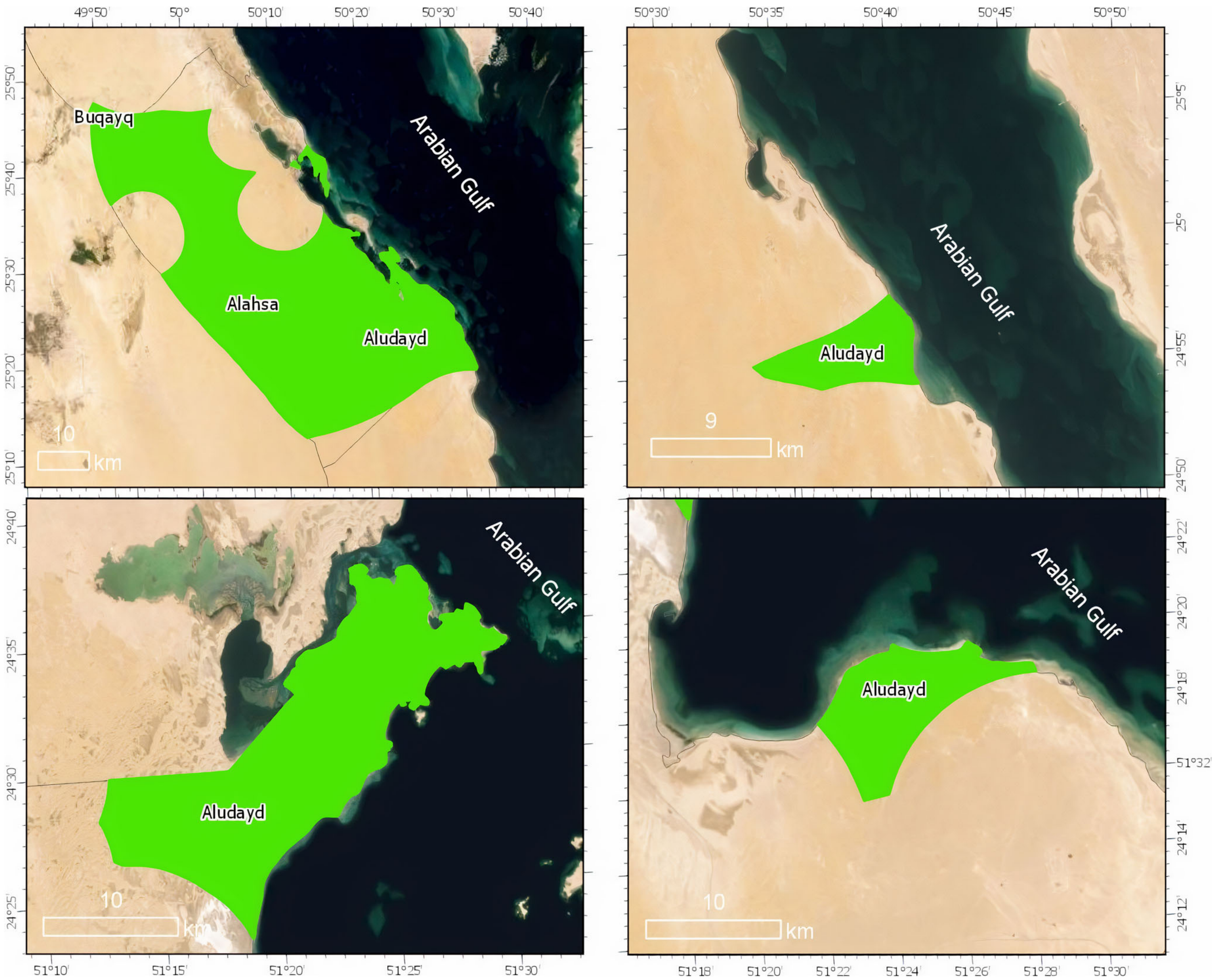


Fig. 11 Final candidate sites on the east coast, including three sites in the Al-Adaid Governorate and one site in Al-Ahsa

local demand for energy. Additionally, the study also recommends examining these candidate areas to determine the best sites specifically for building nuclear power plants in the future.

Future studies

1- To conduct detailed studies for each of the nominated sites using the criteria of comparison (differentiation) to select the best sites and highlighting the appropriate areas located on the eastern coast due to population concentration, economic resources, and petroleum facilities, and its proximity to neighboring countries for the sake of future electricity interconnection or energy export.

2 To conduct studies on the feasibility of investing in the Kingdom's islands for building plants to supply neighboring Saudi cities with their energy needs or exporting electricity abroad to neighboring countries. The analysis has shown the suitability of many islands, which are as follows:

I Al-Numan Island in Duba Governorate
J Four southern islands of Umluj
K Six islands in Al-Leith
L Nine islands in Yanbu
M Three islands in Badr Governorate
N Twelve islands in Al-Qunfudhah Governorate
O Ten islands in Farasan

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